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Implementation of Aerosol Transport and Resuspension Models into the GAMMA+ Code for the Safety Analysis of a VHTR

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1. Introduction

One of the unique features of a Very High Temperature Gas Cooled Reactor (VHTR) is Vented Low Pressure Containment (VLPC) containing two separate vent paths where both have two gravity-operated relief valves in a series. Because VLPC strategy allows the release of a relatively small amount of radioactive fission products(FP) into the environment during the blowdown phase, behavior analyses of the fission products circulating in the primary coolant loop and in the containment are major consideration factors for safety evaluation.

For thermal-fluid analysis of a Very High Temperature Gas Cooled Reactor (VHTR), the GAMMA(GAs Multicomponent Mixture Analysis)+ code[1] is under development. The MAEROS[2,3] model is the multicomponent aerosol module of the CONTAIN code[4], and has been widely used for aerosol behavior analysis. For the first work of FP module development, the MAEROS model had been implemented as an independent module and examined against some analytic solutions and experimental data by Yoo et al.[5] In this study, an aerosol transport model and a turbulent resuspension model were additionally implemented in the FP module of the GAMMA+ code and verified for FP analysis of a VHTR.

2. Implementation and Verification

2.1 Aerosol Transport Model

The MAEROS model analyzes coagulation, growth, and deposition of aerosol only in a single confinement. To make the FP module work properly in the thermal-fluid analyses of a VHTR, it was necessary to simulate inter-cell flow of aerosols. In the inter-cell aerosol transportation, the fission products associated with aerosol component hosts were assumed to flow between cells in proportion to the aerosol component.

In the aerosol transport model, time-dependent evolution of aerosol masses was calculated in two steps. First, the effects of aerosol agglomeration, deposition, and condensation were calculated within a cell neglecting the effects of flow, which process was done by MAEROS model. Second, the effects of flow on the airborne aerosol mass $m_{a,n,j,k}$ of component k in section i and cell n were then calculated from

$$\left[\frac{dm_{a,n,i,k}}{dt}\right]_{flow} = \sum_{jn}\left(v_{a,jn,i}A'_{jn}\frac{m_{a,u,i,k}}{V_u}\right)F_{jn,i} \qquad (1)$$

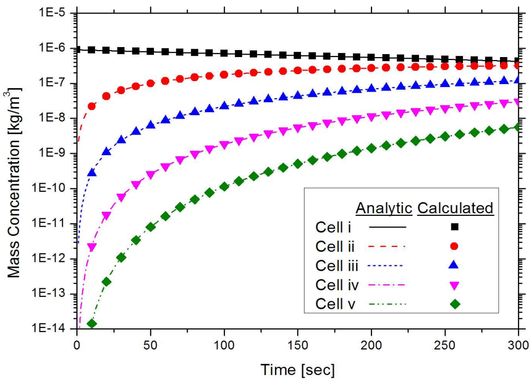
where the sum extends over all gas flow paths connecting cell j to n and the suppression pool vent path, if present; A'_{jn} was the effective flow path area; u denotes the upstream or donor cell; V_u was the cell free volume of donor cell u; and $F_{i,jn}$ was the attenuation factor of the jn path, which depend on flow direction. The aerosol velocity $v_{a,jn,i}$ was equal to the gas velocity minus the aerosol gravitation settling terminal velocity which was zero for horizontal flow direction.

To verify the implemented aerosol transport model, the aerosol transport in a straight pipe was calculated and compared with an analytic solution. To make the problem analytically soluble, it was assumed that all the aerosols were always airborne and would perform coagulation behavior without deposition or condensation. Figure 1(a) shows a schematic of the test problem. Assuming that the attenuation factors F are 1.0 and that there was only one aerosol component; equation (1) can be simplified as

$$\left.\begin{aligned} \frac{dm_1}{dt} &= -\alpha_1 m_1 \\ \frac{dm_2}{dt} &= \alpha_1 m_1 - \alpha_2 m_2 \\ &\cdots \\ \frac{dm_5}{dt} &= \alpha_4 m_4 - \alpha_5 m_5 \end{aligned}\right\} \qquad (2)$$

Here, the subscripts i's for m were cell numbers and the subscripts i's for α are junction numbers. $\alpha_i = v_i A'_i / V_u$ were constant for this case.

(a) Test geometry and nodalization



(b) Comparison with an analytic solution

Fig. 1. Aerosol transport calculation for a flow velocity of 0.01 m/s without deposition or condensation.

The analytic solutions of this set of linear differential equations were

$$\left.\begin{aligned} m_1(t) &= m_{1,0}e^{-\alpha t} \\ m_2(t) &= \alpha m_{1,0}te^{-\alpha t} \\ m_3(t) &= \alpha^2 m_{1,0}t^2 e^{-\alpha t}/2 \\ m_4(t) &= \alpha^3 m_{1,0}t^3 e^{-\alpha t}/6 \\ m_5(t) &= \alpha^4 m_{1,0}t^4 e^{-\alpha t}/24 \end{aligned}\right\} \qquad (3)$$

From Fig. 1(b), we can see that the calculated results were exactly matched with the analytic solutions. Therefore, it was concluded that the implemented aerosol transport model has been verified successfully.

2.2 Turbulent Resuspension Model

Turbulent resuspension of deposited aerosol particles has been modeled as a power law curve fit to the experimental data obtained at the ORNL aerosol resuspension test (ART) facility.[6] The fractional rate of resuspension, F [/s], was expressed as

$$F = 0 \quad \text{when } Re < 2300 \qquad (4)$$

$$F = 0.05\tilde{v}^2 t^{-1.25} \quad \text{when } Re > 2300 \qquad (5)$$

where $\tilde{v}$ was a friction velocity, and t was the time measured from the point when Re first exceeds 2300. The same assumptions that used in VICTORIA 2.0 code[6] were applied. It should be noticed that the ART data were based on dry powders, i.e., aerosols that contain no liquid component during deposition or resuspension.

For verification, effects of resuspension have been tested in a straight pipe (Fig. 1(a)) depending on varying Reynolds number from flow velocities of 0.02 m/s to 0.2 m/s. To accelerate convergence at higher flow velocities, number of the cells in the block was increased to 10. Table 1 summarizes the effects of resuspension on airborne aerosol mass concentrations and cumulative aerosol depositions of each cell at 300 second. When Re = 1021, the fractional rate of resuspension F becomes zero from equation (4) and the aerosol mass concentration and cumulative deposition does not change at all. When Re = 5105, the resuspension model was activated and airborne aerosol concentrations increase generally. Aerosol cumulative depositions decrease in the upstream cells but increase in the downstream cells, because airborne aerosol mass gain due to upstream resuspensions forces aerosol deposition exceeding resuspension losses of the applied cells. By this test calculation, the implemented turbulent resuspension model has been verified qualitatively to work properly according to a varying Re number.

3. Conclusions

An Aerosol transport model and a turbulent resuspension model were implemented and successfully verified in the aerosol analysis module of the GAMMA+ code for simulating inter-cell flow of aerosols. In the future study, these models will be validated against available experimental data and improved for inclined pipe flows.

Acknowledgement

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Table 1. Airborne aerosol mass concentrations and cumulative depositions with and without resuspension model. (t = 300 s)

Cell No.	Without Resuspension		With Resuspension		$\frac{C-A}{A}$ [%]	$\frac{D-B}{B}$ [%]
	Aerosol Concentration [kg/m^3], **A**	Deposited Aerosol Mass [kg], **B**	Aerosol Concentration [kg/m^3], **C**	Deposited Aerosol Mass [kg], **D**		
Re = 1,021						
1	1.9527e-7	1.0388e-6	1.9527e-7	1.0388e-6	0	0
2	1.9763e-7	2.7003e-7	1.9763e-7	2.7003e-7	0	0
3	1.0971e-7	8.4058e-8	1.0971e-7	8.4058e-8	0	0
4	4.1442e-8	2.2907e-8	4.1442e-8	2.2907e-8	0	0
5	1.1887e-8	5.1921e-9	1.1887e-8	5.1921e-09	0	0
6	2.7616e-9	9.7857e-10	2.7616e-9	9.7857e-10	0	0
7	5.3984e-10	1.6157e-10	5.3984e-10	1.6157e-10	0	0
8	9.1157e-11	2.4279e-11	9.1157e-11	2.4279e-11	0	0
9	1.3557e-11	3.2612e-12	1.3557e-11	3.2612e-12	0	0
10	1.8025e-12	3.9613e-13	1.8025e-12	3.9613e-13	0	0
Re = 5,105						
1	9.4684e-9	7.1761e-7	9.4804e-9	7.1754e-7	0.1267	-0.00948
2	1.0310e-8	3.2979e-7	1.0326e-8	3.2977e-7	0.1542	-0.00576
3	2.1792e-8	2.1080e-7	2.1809e-8	2.1079e-7	0.0789	-0.00576
4	4.0292e-8	1.5312e-7	4.0309e-8	1.5311e-7	0.0417	-0.00196
5	5.8721e-8	1.1364e-7	5.8736e-8	1.1364e-7	0.02554	-0.00088
6	6.9433e-8	8.1875e-8	6.9445e-8	8.1874e-8	0.01757	-0.00024
7	6.8845e-8	5.5710e-8	6.8854e-8	5.5711e-8	0.01307	0.00054
8	5.8701e-8	3.5929e-8	5.8707e-8	3.5930e-8	0.01039	0.00056
9	4.3981e-8	2.1455e-8	4.3985e-8	2.1456e-8	0.00864	0.00140
10	2.9362e-8	1.2022e-8	2.9365e-8	1.2022e-8	0.00749	0.00083